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BUTRUS T. KHURI-YAKUB					
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ANNUAL SUMMARY REPORT JUNE 1, 1995 TO MAY 31, 1996

A. Description of Project

The objective of the Micromachined Ultrasonic Transducer (MUT) development effort is to generate practical fabrication procedures and robust theoretical models of novel ultrasonic sensors and actuators. These transducers should constitute a superior alternative to conventional piezoelectric devices in many applications. Although each unique application will most likely require its own optimized version of a MUT, the general principles and design rules elucidated by the development effort should impact the areas of hydrophonics, non destructive evaluation, medical imaging, ranging, flow metering, and even scanning tip imaging and lithography.

B. Approaches Taken

MUT development begins in the broadest sense with the definition of a thought paradigm. It is most productive to concentrate on the displacement of the surface of the transducer in the medium of interest and on the frequency dependence of such displacement. All other quantities (i.e. power, velocity, pressure, etc.) can be derived. The challenge is thus reduced to one of maximizing the surface displacement that a unit of electrical power will generate, and, conversely, maximizing the electrical signal that a unit of acoustic displacement will generate. The qualitative answer to the challenge is that as little kinetic energy as possible should be associated with the displacement of the unloaded transducer surface. Thus, when the transducer is loaded by a fluid, the fluid receives a large fraction of the energy. Specifically, the surface should be that of a very light membrane so that the kinetic energy associated with its motion is low. Furthermore, all dimensions should be very small so that low levels of electrical potential energy (voltage) translate to large forces and consequently to large displacements.

The best way to fabricate very small, light structures repeatably and in a controlled manner is to borrow from the standard techniques pioneered by the integrated circuit industry. Thus, micromachining is the chosen vehicle of device fabrication, with the added benefit that production for industrial and military applications would enjoy a low cost structure.

More sophisticated concepts, such as equations of motion, Green functions, impedance formulations, and ABCD matrices are used to develop computer simulations of device behavior. Finite element code is also being explored to aid in design optimization.

When the transducer design is validated by preliminary calculations, process development is undertaken. When process development results in viable devices, test beds are generated, including supporting electronics, in order to compare the true performance of the devices to theory. If necessary, an optical interferometer can be used to measure the displacement at the transducer surface directly. Then, the device design, the theory, and the process are revised so that the subsequent generation of transducers is improved.

C. Accomplishments

Standard micromachining techniques have been used to fabricate transducers with resonant frequencies in the 1 to 12 MHz range in air. Transmission experiments have been performed repeatedly in air. Of particular interest is the dynamic range of the devices. Noise floor models have been developed and low noise circuits have been built which imply that displacements on the order of 0.01 \AA are detectable with a 4 mm^2 device (the detection floor scales inversely to the square root of device area). Thus, emission displacements on the order of 1000 \AA should result in 100 dB of dynamic range. The linear transmission dynamic range of 4 mm^2 devices was found to be 80 dB at 3.6 MHz. Non-linear effects in air account for the discrepancy, and preliminary calculations using Blackstock's excess attenuation formulations agree with the experimental results. The 80 dB dynamic range was large enough to permit through transmission with Plexiglas. Ultrasound was excited in, and detected from Plexiglas at 5 MHz using air as the coupling medium. Also, accurate detection of a $25 \text{ }\mu\text{m}$ step height was made with a pulse-echo line scan at 3.6 MHz. A dynamic range of 100 dB is still theoretically attainable with larger area devices and at lower frequencies, and further experiments await new lower frequency transducers. Presently, a theoretical model incorporating non-linear effects is being developed. A section of the next submitted paper (a submission is planned for the special transducers issue of the *IEEE Transactions on UFFC*) will be dedicated to the non-linearity issue.

Although the evidence of the non-linear behavior constrains the linear dynamic range of airborne transmission, it opens up new areas for applications.

If acoustic power on the order of tens of mW/cm^2 can be generated, then a streaming jet results. Such a streaming jet could be used to perturb the boundary layer on airplane wings or projectiles and reduce friction. Operation of MUTs in the previously reported "knocking mode" is perhaps the best way to maximize ultrasonic power coupling into air. The streaming phenomenon will be considered further, once we finish the main transducer development effort.

Both the theory and the fabrication process have been modified for the development of immersion transducers. The theoretical model predicts a transmission dynamic range as high as 160 dB in water when electronic noise is taken to be dominant. The fundamental thermal noise of the membrane in water is indeed lower than that of the electronics. It may be possible to reduce the electronic noise, further widening the dynamic range. Perhaps more significantly, theoretical simulations predict very broadband behavior (from hundreds of kHz to tens of MHz).

A fabrication process has been developed to generate vacuum sealed hexagonal elements. The hexagonal structure is chosen because it yields closely packed matrices with a maximum ratio of active area to inactive support. The fabrication process consists of a simple combination of standard micromachining techniques, and is the subject of a current patent disclosure. This fabrication process yields matched transducers repeatably. The transducers work both in air and in water.

Recently, the first transmission of ultrasound in water using MUTs was verified. The same pair of MUTs was able to send and receive signals from 1 MHz to 16 MHz, which was the limiting bandwidth of the electronics. An article is being written for submission to *Applied Physics Letters*.

The accomplishments achieved in this reporting period pave the way for many interesting investigations in the coming year. Among them are the fabrication and modeling of focused transducers in both air and water. Ultrabroadband air transducers will also be fabricated. The frequency range of the immersion transducers will be pushed on both the high and the low end (below 1 MHz and above 16 MHz). Finite element simulations will also be run on the hexagonal structures. The "knocking mode" of operation will be investigated more closely. And finally, if time and resources permit, the streaming phenomenon and the scanning tip force sensor will be investigated. The development effort has significant implications in the areas of medical ultrasound, underwater detection, non-destructive evaluation (manufacturing, materials

characterization, and infrastructure inspections), flow metering, and position sensing.

OFFICE OF NAVAL RESEARCH
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for

01 June 95 through 31 May 96

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Principal Investigator: Butrus T. Khuri-Yakub

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- a. Number of Papers Submitted to Referred Journal but not yet published: 1 (in preparation)
- b. Number of Papers Published in Referred Journals: 2
- c. Number of Books or Chapters Submitted but not yet Published: 1 (in preparation)
- d. Number of Books or Chapters Published: 0
- e. Number of Printed Technical Report & Non-Referred Papers: 2 (in preparation)
- f. Number of Patents Filed : 3 (in preparation)
- g. Number of Patents Granted: 0
- h. Number of Invited Presentations at Workshops or Prof. Society Meetings: 1
- i. Number of Presentation at Workshop of Prof. Society Meetings: 1
- j. Honors/Awards/Prized for Contract/Grant Employees: 1
- k. Number of graduate students supported at least 25% this year this contract/grant: 1
- l. Number of post docs supported at least 25% this year this contract/grant: 0

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OFFICE OF NAVAL RESEARCH
PUBLICATION/PATENTS/PRESENTATION/HONORS REPORT

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Papers published in refereed journals:

1. I. Ladabaum, B. T. Khuri-Yakub and Dimitri Spoliansky, "Micromachined Ultrasonic Transducers (MUTS): 11.4 MHz Transmission in Air and More," Appl. Phys. Lett. 68, 7 (Jan. 1, 1996).
2. M. Haller and B. T. Khuri-Yakub, "A Surface Micromachined Electrostatic Ultrasonic Air Transducer," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 43, No. 1, January, 1996, pages 1-6.

Printed Technical reports & non-refereed papers

1. D. Spoliansky, I Ladabaum and B. T. Khuri-Yakub, "Micromachined Ultrasonic Transducers (MUTS)" Microelectronic Engineering 30 (1996) 535-538, J. Perrocheau Editor, Elsevier. Presented at the International Conference of Micro- and Nano-Engineering, Aix en Provence, France, September 26-28, 1995.
2. I. Ladabaum, B. T. Khuri-Yakub, D. Spoliansky and M. I. Haller, "Micromachined Ultrasonic Transducers (MUTs)," Proceedings IEEE Ultrasonics Symp. Vol. 1, IEEE cat. no. 95CH35844, Ed. M. Levy, S. C. Schneider, and B. R. McAvoy, 501-504 (Inst. of Elec. and Electronics Engineers, Inc., NY 1995).

Invited presentations at workshops or professional society meetings:

1. B. T. Khuri-Yakub, "Ultrasonic Air Transducers and their Applications," presented at ASNT School, June 26 to June 30, 1995, to be published as a chapter in the book of the ASNT School on Sensors for Process Monitoring and Quality Control.

Contributed presentations at workshops or professional society meetings:

1. B. T. Khuri-Yakub I. Ladabaum and D. Spoliansky, "Micromachined Ultrasonic Air Transducers," presented at Review of Progress in Quantitative NDE at the University of Washington, Seattle, Washington, July 30, to August 4, 1995.

Honors/awards/prizes for contract/grant employees, such as scientific society and faculty awards/offices:

Best paper award for the following paper which was presented in Aix en Provence:

D. Spoliansky, I Ladabaum and B. T. Khuri-Yakub, "Micromachined Ultrasonic Transducers (MUTS)" *Microelectronic Engineering* 30 (1996) 535-538, J. Perrocheau Editor, Elsevier. Presented at the International Conference of Micro- and Nano-Engineering, Aix en Provence, France, September 26-28, 1995.